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Numerical evaluation of sample size effect on the stress-strain behavior of geotextile-reinforced sand

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Abstract: This paper studies the effect of sample size on the stress-strain behavior and strength characteristics of geotextile reinforced sand using the finite element numerical analysis. The effect of sample size was investigated by studying the effects of varying the number of geotextile layers, the confining pressure and the type of geotextile. Modeling was performed on samples with five different diameters: 38, 100, 200, 500 and 600 mm. The elastic-plastic Mohr-Coulomb model was used to simulate sand behavior. Results showed that small-sized samples show higher values of peak strength and higher axial strain at failure in comparison with large-sized samples. The size effect on the behavior of samples became further apparent when the number of geotextile layers was increased or the confining pressure was decreased. In addition, the results indicated that the magnitude of the size effect on the mechanical behavior of reinforced sand decreases with an increase in the sample size.

Key words: Reinforced sand, Geotextile, Peak strength, Mohr-Coulomb, Size effect
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1 Introduction

Reinforced soil is a composite material in which elements of high tensile resistance are implemented to increase the tensile resistance of the soil. Geosynthetics are the main materials used for increasing the resistance and stability of geotechnical structures all around the world. Among geosynthetics, geotextiles have received more attention because of their wide range of usage (Holtz, 2001).

One of the most important applications of geotextiles is in the construction of reinforced slopes to increase the shearing resistance and allow for steeper slopes to be designed and constructed. The methods used to design reinforced slopes are based mainly on the limit equilibrium concept. Methods such as Jewell (1980; 1991), Reugger (1986), Schmertmann *et al*. (1987), Leshchinsky and Boedcker (1989), and Michalowski (1997) all use limit equilibrium analysis or limit analysis in the design of reinforced slopes. These studies used different methods in their analyses: the method of slices, two-part wedge and internal stability, variational limit equilibrium, and kinematics limit analysis, respectively.

Since the early 1970s, several investigators have studied stress-strain and strength characteristics of reinforced soil using triaxial, direct shear, and plane strain tests. Since 1977, extensive work has been performed on geotextile-reinforced sand. Some of these investigations are reviewed here to provide a reference to existing experimental data on the behavior of reinforced soils. Broms (1977) researched the mechanical behavior of geotextile-reinforced sand with monotonous grain size using a number of triaxial tests. Borms (1977) also studied the effect of distance between geotextile layers, sand density, and confining pressure on the strength of reinforced sand samples.

McGown *et al*. (1978) carried out a series of plane strain unit cell tests on dry sand samples reinforced with aluminum foil, aluminum mesh, and a nonwoven geotextile. They concluded that there are important differences between the behavior of a relatively low stiffness geotextile and high stiffness aluminum. The former was characterized as an ideal extensible material. This type of reinforcement resulted in some strengthening but more significantly gave greater extensibility (ductility) and a smaller loss of post-peak strength when compared to the soil alone or to the sand reinforced with high stiffness metal.

Holtz *et al.* (1982) conducted a number of long-term and short-term triaxial tests on dry sand reinforced by woven and nonwoven geotextiles. They also observed the influence of reinforcement on the creep of reinforced samples. Nakai (1992) investigated the stress-strain behavior of reinforced sand using triaxial tests and finite element analysis. Triaxial tests were performed on Toyoura sand, and reinforcement layers in the form of brass sheets were employed. Some finite element analyses were also performed under the experimental conditions with only a quarter of the triaxial samples being modeled. Krishnaswamy and Isaac (1995) investigated the liquefaction susceptibility of geotextile-reinforced sand by conducting some cyclic tests. The tests were performed on 38-mm and 76-mm diameter sand samples with uniform grain size to determine the strength of the samples against liquefaction. Haeri *et al*. (2000) studied the mechanical behavior of nonwoven geotextile-reinforced sand using triaxial apparatus. They conducted 160 triaxial tests on unreinforced and reinforced Babolsar dry sand. They investigated the effect of some determining factors including geotextile layers, type and orientation of geotextiles and confining pressure. Two samples, with 38 and 100 mm diameters respectively, were tested to determine the influence of sample size on the mechanical behavior of unreinforced and reinforced sands.

Many studies have been carried out to understand the beneficial effect of reinforcement layers in sand using geosynthetics, including Gray and Ohashi (1983), Chandrasekaran *et al*. (1989), Morel and Gourc (1997), Temel *et al*. (2003), Latha and Murthy (2007), and Zhang *et al*. (2006; 2008). In comparison with the experimental research, only a few numerical studies are available on the application of geosynthetics to reinforce sand, including Adachi and Poorooshasb (1988), Sawicki and Lesiniewska (1992), Nakai (1992), and di Prisco and Nova (1993).

Thus, there is an urgent need for numerical modeling of sand reinforced with geotextile. Performing experimental studies on reinforced soil is a tedious task for several reasons. First, performing each test requires a great amount of time for sample preparation as well as for carrying out the test. Second, performing numerous tests to study the effect of different parameters can be quite costly. Third, carrying out complex experimental tests requires constant control of test procedures to prevent human errors and misinterpretation of results. Finally, owing to the limitations of sample size in experimental setups, the results obtained in the laboratory are often affected by sample size. However, numerical modeling of the experiments provides an attractive alternative for actual testing, since modeling of even complex tests can be achieved in a fraction of the time required for performing actual tests. Numerical results, if consistent with actual observations, can be quite reliable, as the sources of error in actual experimental testing are eliminated. Moreover, the cost of performing numerous numerical analyses is often much lower than that of actually carrying out the tests in a laboratory. Most importantly, however, the samples in numerical simulations are not restricted by size, and the effect of sample size can easily be studied. Given these advantages, in this study a numerical investigation was carried out to investigate the behavior of reinforced sand in a triaxial apparatus. The modeling techniques employed are described, followed by a validation of methods through simulation of actual triaxial tests on unreinforced as well as reinforced sand samples. Finally, the sample size effect is studied through numerical parametric analysis, and the results are interpreted to gain insight into the effect of sample size on the behavior of reinforced sand in triaxial tests.

2 Modeling procedure

In this project the finite element software, PLAXIS (Vermeer and Brinkgreve, 1998), was employed to model geotextile reinforced sand in a triaxial apparatus. Because of the circular cross section of the sample and the confining pressure, the analytical axisymmetric method can easily model the conditions of a triaxial test, and was therefore employed in the numerical modeling. To create the geometry of the reinforced sand sample, a model with H/D=2, where H is the model height and D is the diameter of the sample, was built. It is important to note that only one half of the sample diameter has been modeled because of the axisymmetric conditions. Since the left side of the sample is the axis of symmetry, the horizontal displacement of the sample along this axis is zero, whereas the upper and lower boundaries are free to move. The geotextile layers are modeled using 1D geotextile structural elements available in the commercial code, which requires the specification of EA as geotextile properties, where E represents the axial stiffness and A is the cross sectional area of the geotextile. Soil-geotextile interaction is modeled by employing interface elements, with interface properties represented through the coefficient R_{int}, which is multiplied by the mechanical properties of the soil to give interface properties.

In this study, loading of the sample is applied in two stages. In the first stage, the confining pressure is exerted on the upper, lower and right sides of the sample (the first stage of the triaxial test, as shown in Fig. 1a). The next step is to create proper conditions for shear loading in the sample, which is produced by a specified movement in the sample (the second stage of the triaxial test) such that constant movement in the form of a specified percentage of the sample height is exerted on the two ends of the sample (Fig. 1b).

After carrying out the numerical analysis, the mean deviating stress is calculated throughout the sample, which is the sample peak resistance in the triaxial test. For a given confining pressure and a number of geotextiles, the displacement is increased at a constant rate up to 15% of the sample height. The deviator stress and rupture strain are also calculated. The experiment is then repeated for different confining pressures and numbers of geotextile layers.

3 Geotextile arrangement and confining pressure

The effect of the number of geotextile layers on the mechanical behavior of reinforced sand of five different forms was investigated. Fig. 2 shows the arrangement of geotextiles in reinforced samples. Arrangements of one, two, three or four layers of geotextiles were considered for the reinforced samples, while an unreinforced sample was also tested to provide a basis for comparison and assessment of the effects of reinforcing on the behavior of the soil.

To evaluate the effect of confining pressure on the stress-strain behavior of unreinforced and reinforced sand types, four confining pressure values of 60, 100, 300, 500 kPa were considered.

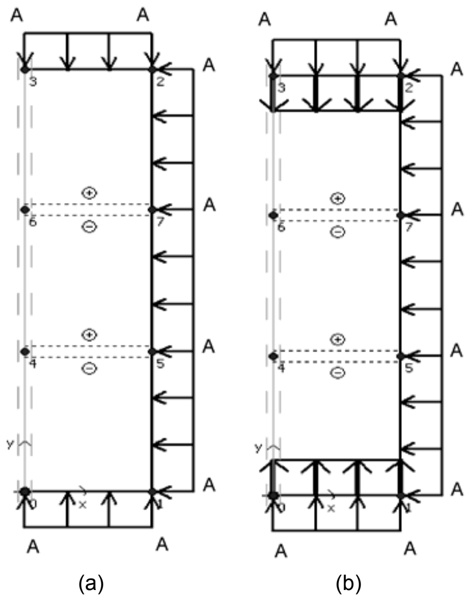

Fig. 1 Numerical simulation of geotextile reinforced sand sample in PLAXIS
(a) Application of confining pressure; (b) Application of deviator stress

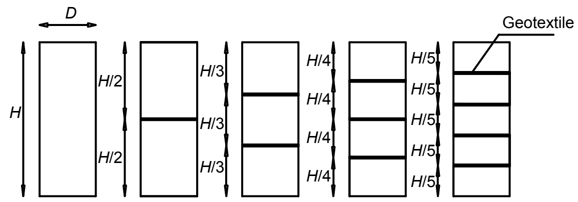

Fig. 2 Geotextile arrangements in reinforced sand sample
H is the model height, and D is the diameter of the sample

4 Material properties

In this section, the strength properties of sand required for numerical analysis and the mechanical properties of the geotextile are presented. To determine the strength properties of sand, the triaxial test results on the unreinforced sand sample were used. To determine the elasticity modulus of sand, the axial stress-strain curve of the unreinforced sand sample was implemented at every confining pressure value (tangent modulus). The strength properties of the sand are shown in Tables 1 and 2. The reinforcement consists of two geotextiles, namely geotextile types I and II. The mechanical properties of these geotextiles are shown in Table 3, where *EA* is the stiffness of the geotextile in the load-displacement curve, and R_{int} is the ratio between the friction angles of geotextile and sand (Haeri *et al*., 2000).

Table 1 Strength characteristics of sand

Parameter	Value
r_d (kN/m^3)	18.6
Cohesion (kPa)	0.25
Shear strength angle (°)	44
Dilatancy angle (°)	4
Poisson's ratio	0.305

r_d: relative density

Table 2 Elastic modulus of sand for various confining pressures

Confining pressure (kPa)	Elastic modulus (kPa)
60	11000
100	15500
300	27500
500	33000

Table 3 Mechanical properties of geotextiles

Type of geotextile	*EA* (kN/m)	Friction angle between geotextile and sand (°)	R_{int}
I	33.10	37.1	0.78
II	20.75	38.7	0.83

5 Results and discussion

In this section, the results of the numerical analysis of the size effect on the unreinforced and geotextile-reinforced sand are assessed by presenting different curves and diagrams. In presenting and discussing the results, the parameter 'residual strength ratio' is employed, which is the ratio of the strength at 15% axial strain to the peak strength. The effects of sample size on peak strength, stress-strain behavior, residual strength ratio, and the failure envelope are assessed.

5.1 Size effect on peak strength of unreinforced sand

The size effect on the peak strength of unreinforced sand samples is shown in Fig. 3. The peak strength for 38-mm and 100-mm diameter samples and various confining pressures are approximately equal. More specifically, the peak strength of the 38-mm diameter sample is only marginally greater than that of the sample with 100-mm diameter. The greatest difference in peak strength is only 3.9% and is associated with a confining pressure of 500 kPa. This phenomenon is in agreement with the experimental results in (Haeri *et al*., 2000).

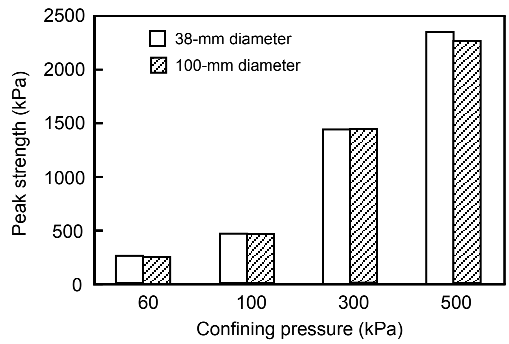

Fig. 3 Size effect on peak strength of unreinforced sand

5.2 Size effect on stress-strain behavior of geotextile-reinforced sand

The effect of sample size on the stress-strain behavior of geotextile-reinforced sand is remarkably different from its effect on unreinforced sand, such that a reinforced sand sample of smaller diameter has a higher peak strength and rupture strain at failure compared to one of larger diameter under the same conditions of geotextile layers and confining pressure (Fig. 4). This is because the confining pressure exerted by geotextile layers, which results in higher peak strength in the reinforced sample, is much greater in the sample with smaller diameter than in the sample with larger diameter. The peak strength of the reinforced sand increases with a decrease in diameter, as also reported by Haeri *et al*. (2000).

Figs. 5 and 6 show the effect of the number of geotextile layers and the confining pressure, respectively, on the size effect of the reinforced sample. The effect of sample size on the stress-strain curve is intensified by an increase in the number of geotextile layers (Fig. 5 and Table 4).

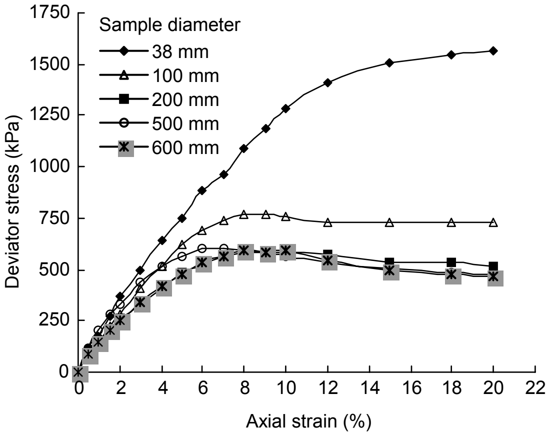

Fig. 4 Size effect on stress-strain curves of reinforced sand with four layers of geotextile under 60 kPa confining pressure

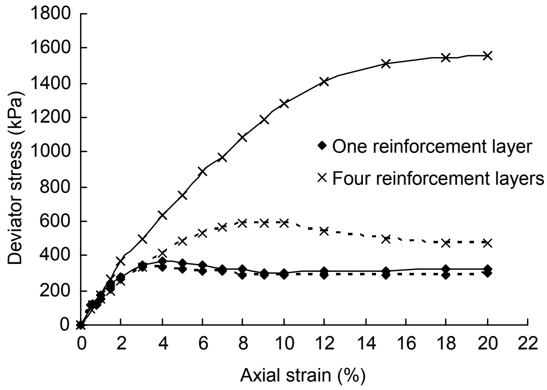

Fig. 5 Effect of the number of geotextile layers on the size effect on stress-strain curves of reinforced sand under 60 kPa confining pressure

Solid line: 38-mm diameter sample; dash line: 600-mm diameter sample

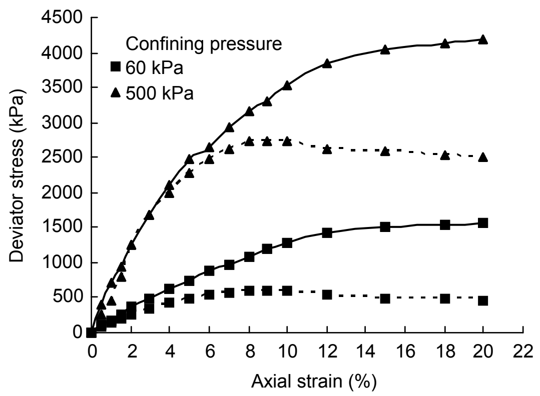

Fig. 6 Effect of confining pressure on the size effect on stress-strain curves of the reinforced sand with four layers of geotextile

Solid line: 38-mm diameter sample; dash line: 600-mm diameter sample

For instance, the sample of diameter 38 mm reinforced by four layers of geotextile and under 60 kPa confining pressure, has a 154.2% peak strength difference compared to the sample of 600 mm diameter. With a single layer of geotextile reinforcement and under the same confining pressure, this difference reduces to 11.4%. The influence of confining pressure on the size effect is shown in Fig. 6 and Table 5. These curves show that the effect of sample size on the peak strength of the reinforced sand decreases with an increase in the confining pressure. For instance, the size effect on peak strength for the sample reinforced by four layers of geotextile and under 60 kPa confining pressure is 154.2%, while this difference for the same number of geotextile layers reduces to 51.8% for 500 kPa confining pressure. This phenomenon was seen for all confining pressures and geotextile arrangements.

Table 4 Effect of the number of geotextile layers on the size effect at the confining pressure of 60 kPa

Number of geotextile layers	Sample diameter (mm)	Peak strength (kPa)	Size effect (%)
One	38	372	11.4
	600	334	
Two	38	748	21.8
	600	614	
Three	38	1060	112.8
	600	498	
Four	38	1505	154.2
	600	592	

Table 5 Effect of confining pressure on the size effect

Confining pressure (kPa)	Sample diameter (mm)	Peak strength (kPa)	Size effect (%)
60	38	1505	154.2
	600	592	
100	38	2116	137.0
	600	893	
300	38	3381	80.4
	600	1793	
500	38	4158	51.8
	600	2740	

5.3 Size effect on residual strength ratio

Fig. 7 shows the relative decrease in strength after the peak pressure. At a constant confining pressure, the residual strength ratio increases with a decrease in diameter. This effect can be traced back to the higher confining pressure caused by geotextile in samples with smaller diameters. The sample of diameter 38 mm has the highest residual strength ratio of all samples, meaning that geotextiles are more efficient in preventing strength loss after the peak strength when samples have larger diameters.

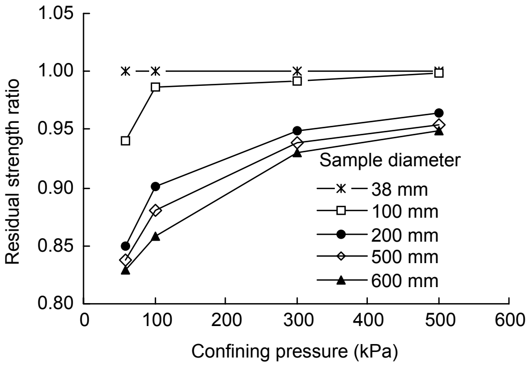

Fig. 7 Size effect on residual strength ratio of the reinforced sand with four layers of geotextile

5.4 Size effect on failure envelope

The failure envelopes for unreinforced and geotextile-reinforced sand types are shown in Figs. 8 and 9. The failure envelopes for unreinforced samples with diameters of 38 and 100 mm almost coincide (Fig. 8). Thus, the sample dimensions do not affect the failure envelope of unreinforced samples. An effect of sample size on the failure envelope for the reinforced samples is remarkably more apparent (Fig. 9). This effect increases with a decrease in the sample diameter. Furthermore, Tables 6 and 7 show the results of the size effect on numerical analysis in this study. The size effect reduces with an increase in the sample diameter and may be ignored for samples diameters of more than 600 mm at high confining pressures and with low numbers of geotextile layers.

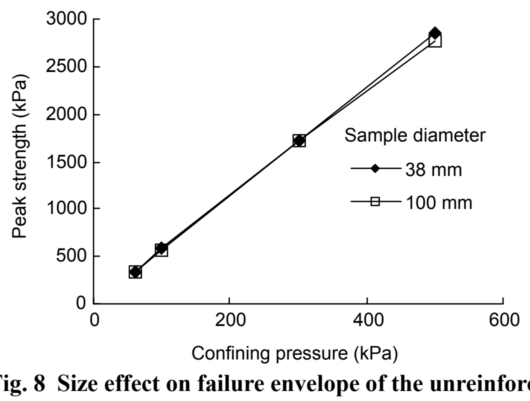

Fig. 8 Size effect on failure envelope of the unreinforced sand

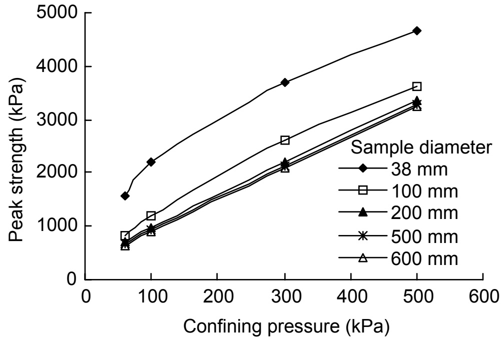

Fig. 9 Size effect on failure envelope of reinforced sand with four layers of geotextile

Table 6 Size effect on peak strength of reinforced samples with four layers of geotextile

Sample diameter (mm)	Peak strength (kPa)			
	60 kPa confining pressure	100 kPa confining pressure	300 kPa confining pressure	500 kPa confining pressure
38	1505	2116	3381	4158
100	771	1088	2296	3102
200	632	878	1895	2854
500	602	816	1828	2792
600	592	893	1793	2740

Table 7 Size effect on peak strength of reinforced samples with one layer of geotextile

Sample diameter (mm)	Peak strength (kPa)			
	60 kPa confining pressure	100 kPa confining pressure	300 kPa confining pressure	500 kPa confining pressure
38	372	680	1717	2606
100	354	603	1682	2533
200	348	589	1556	2493
500	339	570	1524	2459
600	334	561	1498	2413

5.5 Type of geotextile and size effect on failure envelope

Fig. 10 shows the failure envelope for unreinforced sand and sand reinforced with geotextile of either type I or II. The size effect on the failure envelope of the reinforced sand increases with an increase in the friction angle between the sand and the geotextile, since by increasing this angle, the peak strength on the reinforced sand increases.

Clearly, because the geotextile provides a higher confining pressure in samples of smaller diameter, the size effect on the peak strength of samples reinforced by geotextiles of type I is considerably greater than that of samples reinforced by geotextiles of type II. In other words, as the friction angle between the sand and the geotextile increases, the increase of peak strength in samples with smaller diameters is greater compared to that of the samples with larger diameters (Table 8).

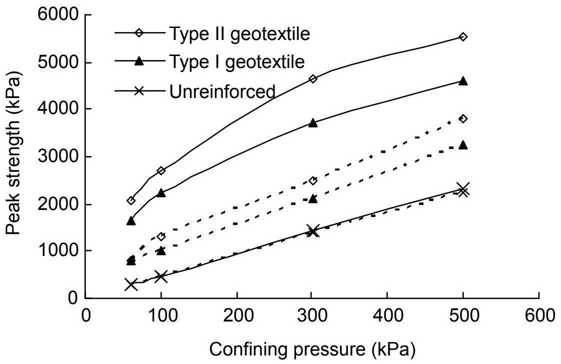

Fig. 10 Size effect on failure envelope of unreinforced and reinforced sand with four layers of geotextile types I and II
Solid line: 38-mm diameter sample; dash line: 600-mm diameter sample

Table 8 Effect of type of geotextile on the size effect with four layers of geotextile

Confining pressure (kPa)	Sample diameter (mm)	Peak strength (kPa)		Size effect (%)	
		Type I	Type II	Type I	Type II
60	38	1505	1923	154.2	192.2
	600	592	658		
100	38	2116	2578	137.0	168. 5
	600	893	960		
300	38	3381	4489	88.6	114.6
	600	1793	2092		
500	38	4158	5037	51.8	59.1
	600	2740	3166		

6 Conclusions

In this paper, a numerical analysis was conducted to study the effect of sample size on different types of geotextile-reinforced sand. Results showed that triaxial tests may be effectively and accurately modeled by means of numerical analysis via the finite element method. Performing triaxial tests on large sized samples using numerical modeling is extremely efficient and economical. The use of numerical modeling of experimental setups for studying the behavior of reinforced soil for practical applications where time and economical restrictions apply provides an attractive alternative to actual experimental testing. This survey has led to the following conclusions:

1. In general, geotextile considerably increases the peak strength and axial strain at failure of reinforced sand. The peak strength is further increased by increasing the confining pressure and the number of geotextile layers.

2. Sample size has a remarkable effect on the mechanical behavior of reinforced sand compared with its effect on unreinforced samples. Hence, the sample of reinforced sand with smaller diameter had a remarkably higher peak strength and axial strain at failure than the sample of reinforced sand with larger diameter, under the same conditions of geotextile layer and confining pressure.

3. The size effect on the peak strength of geotextile-reinforced sand increases with an increase in the number of geotextile layers or a decrease in confining pressure.

4. The size effect on the failure envelope of geotextile-reinforced sand increases with an increase in the friction angle between the sand and the geotextile.

5. The size effect on the failure envelope of reinforced sand decreases remarkably with an increase in sample diameter and may be ignored for samples of diameters greater than 600 mm at a high confining pressure and with a low number of reinforcement layers.

6. The study of the size effect on residual strength indicated that at a constant confining pressure, the residual strength ratio increases with a decrease in sample size. However, with a decrease in sample size the flexibility of the reinforced sand sample increases.

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